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NASA TN D-5648

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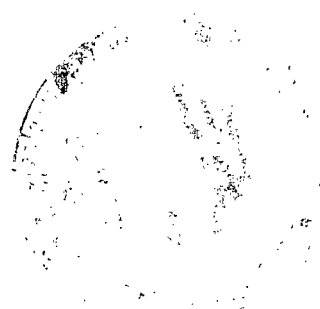
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LOW-GRAVITY LIQUID-VAPOR INTERFACE CONFIGURATIONS IN SPHEROIDAL CONTAINERS

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0132539

1. Report No. NASA TN D-5648	2. Government Accession No.	3. Recipient's Catalog Number	0132539	
4. Title and Subtitle LOW-GRAVITY LIQUID-VAPOR INTERFACE CONFIGURATIONS IN SPHEROIDAL CONTAINERS		5. Report Date February 1970		
		6. Performing Organization Code		
7. Author(s) Jack A. Salzman		8. Performing Organization Report No. E-5304		
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 124-09		
		11. Contract or Grant No.		
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note		
15. Supplementary Notes		14. Sponsoring Agency Code		
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17. Key Words (Suggested by Author(s)) Fluid mechanics; liquid-vapor interface; low gravity; spheroidal containers; weightlessness; liquid surface shape		18. Distribution Statement Unclassified - unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 19	22. Price* \$3.00	

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

LOW-GRAVITY LIQUID-VAPOR INTERFACE CONFIGURATIONS IN SPHEROIDAL CONTAINERS

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SUMMARY

As a part of the general study of liquid behavior in low-gravity environments, an experimental investigation was conducted to determine the equilibrium liquid-vapor interface configuration in oblate spheroidal containers under reduced gravity conditions. Static contact angles of the test liquids on the spheroid surfaces were restricted to near 0° . The experiments were conducted in low-gravity environments ranging from 10^{-5} to 3.1×10^{-2} g and at Bond numbers ranging from effectively zero to 30. Oblate spheroidal tanks were tested with eccentricities of 0, 0.50, 0.68, and 0.80 and semimajor axes of 2.0, 3.0, and 4.0 centimeters. Both quantitative and qualitative data were obtained on the liquid-vapor interface, and these data were compared with previous analytical predictions. Of particular interest were those interface configurations where the tank bottom became void of liquid.

INTRODUCTION

A complete description of the equilibrium liquid-vapor interface is fundamental to any study of the dynamics of a low-gravity, liquid-vapor system. Because of the dependency of the liquid-vapor interface configuration on tank geometry (as well as on other system conditions, such as Bond number, contact angle, and liquid fill level), recent investigations in this area have considered a variety of container shapes such as cylinders, spheres, toroids, and others (refs. 1 to 4). A particularly interesting tank geometry, because of its direct application to current and future space vehicles, is the oblate spheroid (generated by the rotation of an ellipse about its minor axis). Low-gravity interface configurations in oblate spheroids of moderate eccentricity were calculated by different analytical methods in references 5 and 6. Both of these studies considered liquid-vapor systems where the contact angle was at or near 0° . The results of these

separate investigations agree favorably down to a Bond number of 5 which is the lowest value considered in reference 6. Reference 5 presents results for Bond numbers down to zero and predicts that for particular system conditions at low Bond numbers both the top and the bottom of the tank will be void of liquid. To date, no experimental low-gravity data are available to confirm the accuracy of these theoretical predictions.

This report presents the results of an experimental investigation on the liquid-vapor interface configuration in oblate spheroids under low-gravity environments. The liquids used in this study had static contact angles very near 0° on the spheroid surfaces. The experiments were conducted in low-gravity environments ranging from 10^{-5} to $3.1 \times 10^{-2} g$ and at system Bond numbers ranging from effectively zero (i.e., approximately 0.001) to as high as 30. Oblate spheroidal tanks with eccentricity values of 0, 0.50, 0.68, and 0.80 were tested. The experiments were conducted with the liquid initially (i.e., before entry in the low-gravity test environment) in a symmetric position about the tank's semiminor axis (bottomed in the tank). Data on the low-gravity static equilibrium liquid-vapor interface were obtained and compared with previous analytical predictions. Of particular interest were those interface configurations where both the top and bottom of the tank became uncovered. Limited data were also obtained concerning the effect of an initially asymmetric liquid position on the final low-gravity interface position and configuration.

SYMBOLS

- a system acceleration, cm/sec^2
- Bo Bond number, $Bo = ax^2/\beta$
- e tank eccentricity, $e = \sqrt{1 - (y^2/x^2)}$
- g acceleration due to gravity, 981 cm/sec^2
- t time from initiation of low-gravity environment, sec
- x tank semimajor axis, cm
- y tank semiminor axis, cm
- β specific surface tension, ratio of surface tension to density, cm^3/sec^2
- θ static contact angle of test liquid on container surfaces, deg

APPARATUS AND PROCEDURE

Test Facility and Experiment Vehicle

The experimental investigation was conducted in the Lewis Zero Gravity Facility. Data were obtained by allowing a vehicle housing the experiment to free-fall from ground level down a steel vacuum chamber approximately 142 meters deep. This resulted in about 5 seconds of free-fall time. By evacuating the vacuum chamber to a nominal pressure of 13.3 newtons per square meter (1.3×10^{-4} atm), the equivalent gravitational acceleration acting on the experiment due to residual air drag was less than 10^{-5} g. Following the free-fall period, the vehicle and experiment were recovered at the bottom of the chamber in a cart filled with small pellets of expanded polystyrene. Average deceleration of the vehicle during recovery was 32 g's.

The experiment vehicle used in obtaining the data was a completely self-contained unit capable of imparting low-level accelerations on the experiment through use of a cold gas thrust system. When gravity levels other than zero were required, this thrust system was actuated shortly before the vehicle was dropped and was operated continuously through the 5 seconds of low-gravity testing. The system produced low-gravity environments ranging from effectively zero (i.e., less than 10^{-5} g) to 3.1×10^{-2} g.

Data were collected from the experiments by both a high-speed photography system and telemetry which were contained on the experiment vehicle. A more complete description of the facility and test procedures is contained in reference 7.

Test Containers and Liquids

The test containers were oblate spheroids formed from clear acrylic plastic. Eccentricities of these spheroidal tanks - defined as $e = \sqrt{1 - (y^2/x^2)}$ where x and y are the tank semimajor and semiminor axes - were 0, 0.50, 0.68, and 0.80. Three tank sizes were used with semimajor axes of 2.0, 3.0, and 4.0 centimeters. Ethanol, 2-propanol, and FC-43* were employed as test liquids. These liquids had specific surface tensions, respectively, of 28.3, 27.6, and 8.7 cubic centimeters per second squared at 20° C. The alcohols were analytic reagent grade, and the fluorocarbon solvent was a precision cleaning grade. All the liquids had static contact angles of very near 0° on the test container surfaces. Although a small quantity of dye was added to each liquid to improve photographic quality, this dye had no measurable effect on the properties of the liquids pertinent to this study.

The experimental containers were prepared in a clean-room so that contamination

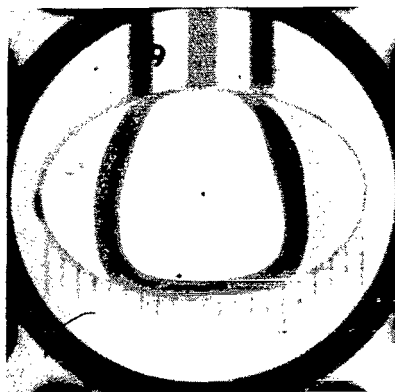
* FC-43 is 3M Company's registered trademark for a fluorocarbon solvent (ref. 7).

of the liquid and the container surfaces, which could alter the surface tension and contact angle, was carefully avoided. The test containers were cleaned ultrasonically in a detergent-water solution, rinsed with a distilled-water - methanol solution, and dried in a warm-air dryer. Immediately prior to a test, the containers were rinsed with the test liquid, filled to the required volume at normal atmospheric conditions, and hermetically sealed in the clean-room. The spheroidal containers were then positioned in the test vehicle with their minor axes parallel to the applied acceleration vector of the vehicle.

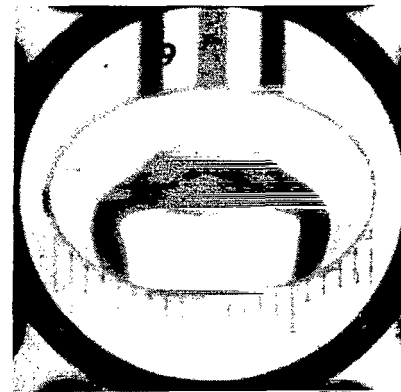
By proper selection of tank size and test liquid in combination with the vehicle acceleration level, it was possible to obtain Bond number environments ranging from effectively zero (i.e., less than 0.001) to as high as 30. The Bond number, a dimensionless parameter characterizing the ratio of acceleration to capillary forces acting in a system, was defined in this program by using the container semimajor axis as the characteristic length dimension (i.e., $Bo = (x^2 a / \beta)$), with the acceleration vector directed through the tank minor axis.



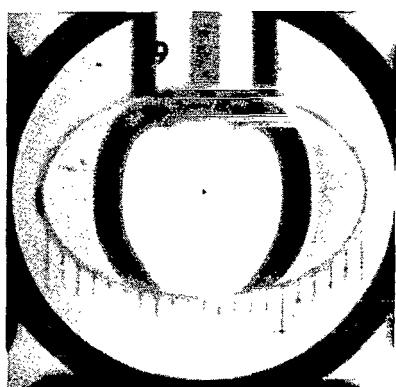
High Bond number configuration;
time, 0 second.



Transient interface shape;
time, 0.21 second.



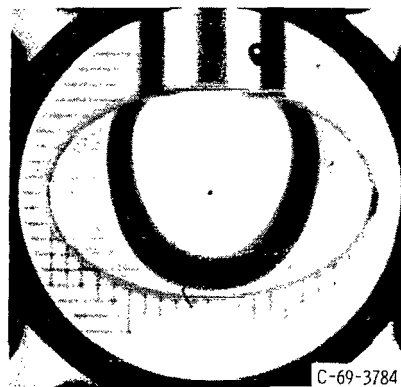
Maximum interface distortion;
time, 0.37 second.



Transient interface shape;
time, 0.69 second.



Completion of first transient oscillation;
time, 0.92 second.



Final interface shape;
time, 4.98 seconds.

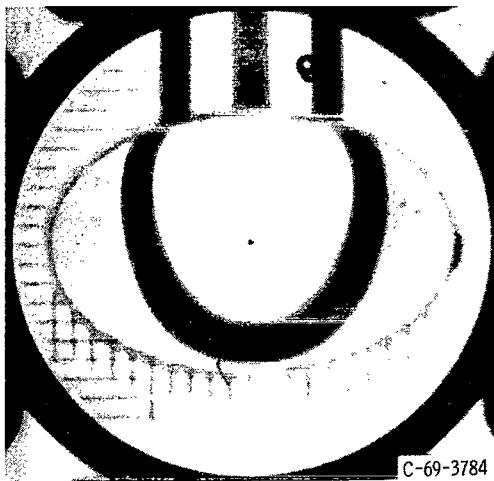
Figure 1. - Transient motion of interface upon entering low gravity. Eccentricity, 0.80; 75 percent filling; Bond number 1; tank semimajor axis, 2 centimeters.

The choice of tank size and test liquid combination was also influenced by low Bond number interface formation time requirements. Useful interface measurements could not be made unless the liquid-vapor system had reached a nearly quiescent equilibrium state before the end of the 5-second test time. On entering a low-gravity environment, the liquid-vapor interface underwent large amplitude motion, oscillating about its reduced Bond number equilibrium position. The amplitude and period of this transient motion was particularly high for the lower Bond number systems (fig. 1). In the test represented in figure 1 the liquid was completely displaced to the top of the tank during the first cycle of oscillation and more than five complete periods of oscillation were required before the motion became sufficiently damped to allow an interface measurement. In many cases, for large tank sizes, this oscillatory motion was not sufficiently damped during the 5-second test period to obtain useful interface data. A reduction in the tank size or an increase in the specific surface tension of the test liquid, or both, would decrease the period of these transient oscillations. By altering tank size and test liquid combinations, it was possible to attain a nearly quiescent interface configuration for most of the systems (i.e., combinations of Bond number, fill level, and tank eccentricity) which were considered.

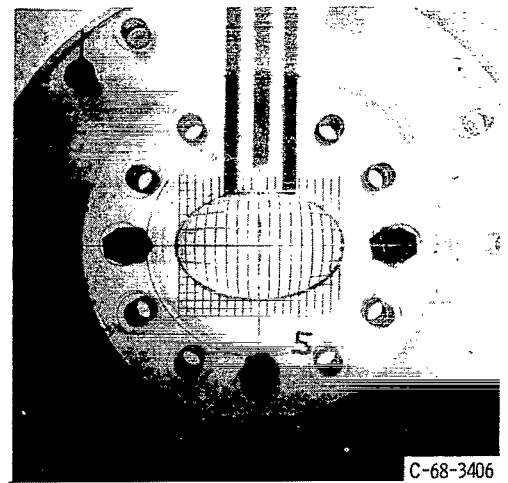
Data Analysis

The liquid-vapor interface configuration data obtained in this investigation were taken from color data film by use of a motion picture film analyzer which magnified the image by a factor of 25. From both the tank scales and a set of vernier crosshair readings, the observed interface shape was plotted as in figure 2. Because of optical distortions due to refraction, it was necessary to correct these data to obtain the true liquid-vapor interface shape and position. The refraction correction procedure that was employed is illustrated in figure 2. A calibration photograph consisting of an 8- by 10-inch positive transparency was made of each container-liquid combination with an etched grid positioned along the spheroid centerline (i.e., in a plane containing the tank minor axis). The large degree of distortion encountered is shown in a typical calibration photograph (fig. 2). By tracing the observed interface coordinates to their true position as represented on the calibration grid, the actual interface position and configuration was determined. This direct approach of refraction correction was employed rather than using refraction calculation schemes because of random irregularities in the container wall thickness.

As seen in figure 2, it was not possible to measure the entire curvature of the liquid-vapor interface. This was because of critical refraction losses which were particularly high near the tank wall. These refraction losses also frequently prohibited the



Original data photograph



Refraction calibration photograph

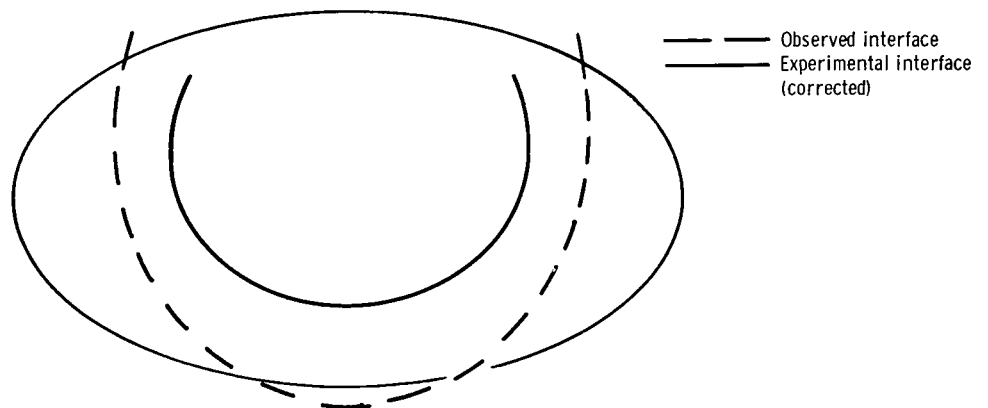


Figure 2. - Correction procedure for interface data.

measurement of the liquid edge position where it intersected with the tank wall. When measurements of this edge position were possible, they could generally be performed with a greater degree of accuracy than those measurements of the interface near the center of the tank. In the data photographs, the general outline of the interface was defined by a dark band (figs. 1 and 2). The actual interface shape follows the outer perimeter of this dark band and was generally difficult to define because it was observed through a depth of liquid in some cases as large as the semimajor axis of the tank.

RESULTS AND DISCUSSION

Comparison of Experimental Results and Theoretical Predictions

The quantitative interface configuration data obtained in this investigation are presented in the appendix. Accompanying the experimental interface shapes in each plot in the appendix are the predicted shapes as calculated in reference 5. These predicted shapes from reference 5 were based on a 5° contact angle condition while the shapes presented in reference 6 considered 0° contact angles. Because the results of these two theoretical studies agree quite well down to a Bond number of 5 (the lowest value attempted in ref. 6) it would be redundant to present both sets of predictions for comparison purposes. The predicted shapes from reference 5 are used exclusively in the appendix because they cover the widest available range of low Bond number predictions.

As presented in the appendix, the data of this investigation agree favorably with the previous analytical predictions (refs. 5 and 6). In general, the experimental liquid-vapor interface shapes followed the calculated curvatures but were slightly displaced from the predicted interface position. This position discrepancy must be considered within the experimental error range due to the measurement difficulties previously discussed.

In addition to the quantitative data presented in the appendix, a number of qualitative observations were also made which were useful in comparing the experimental results with the theoretical predictions. No quantitative measurements were taken in spheroids of zero eccentricity (i.e., spheres). Interface configurations in this tank shape have been documented both analytically and experimentally (e.g., refs. 2 and 3). Limited qualitative data taken in spheres in this investigation agreed with those of these previous studies and no further effort was expended in this direction.

Additional qualitative observations were made in the present investigation whenever refraction losses completely prohibited acquisition of quantitative data. These observations were particularly useful in defining those system combinations where the interface shape uncovers the tank bottom. As predicted in reference 5, particular system combinations of low Bond numbers, low fill levels, and high tank eccentricities can result in liquid-vapor interface configurations where both the top and the bottom of the tank became uncovered and the liquid is positioned in an annular channel around the perimeter of the tank. This occurs primarily at low fill levels where the liquid-vapor interface is near the tank wall; thus, it was difficult to determine whether the tank bottom was or was not actually covered with liquid because of critical refraction losses. In most cases, the depth of the liquid layer on the tank bottom could not be measured quantitatively but could be observed quite easily on the data film.

All those system combinations, located near the predicted region where the liquid

bottom first becomes uncovered, were investigated by employing a composite of quantitative measurements and qualitative observations. These experimental transition regions where the liquid formed an annular type of interface agree with those predicted in reference 5 and are summarized as follows:

Tank eccentricity	Bond number	Fill level, percent	Tank bottom -
0.50	0	≤ 25	Uncovered
	≥ 1	$a \geq 12.5$	Covered
0.68	0	≤ 37.5	Uncovered
	≥ 1	$a \geq 12.5$	Covered
0.80	0	≤ 62.5	Uncovered
	1	≤ 37.5	Uncovered
	2	≤ 12.5	Uncovered
	≥ 5	$a \geq 12.5$	Covered

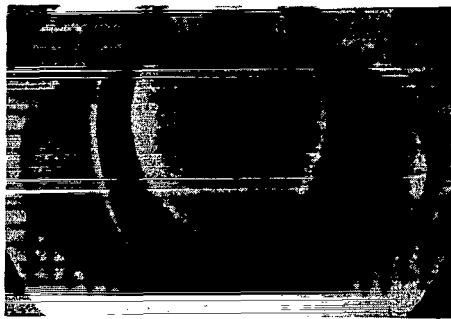
^aLowest volume tested.

Effects of System Parameters on Interface Configurations

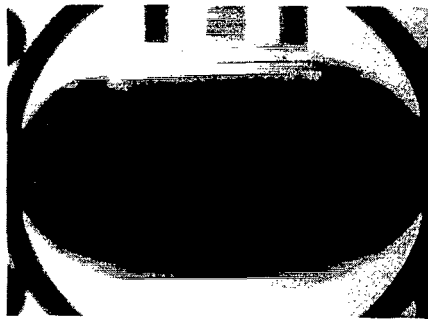
Effects of Bond number. - The effects of varying the Bond number on the interface shape at both high and low fill levels are illustrated in figures 3 and 4. The interface plots presented in these and the following figures are taken from reference 5 because of their completeness. As previously stated, the experimental interface shapes did agree favorably with those predicted in reference 5, and therefore the plots presented in each figure are representative of the actual interface configurations as seen in the accompanying data photographs.

At high fill levels (fig. 3), increasing the system Bond number simply decreases the interface curvature. At very low Bond numbers, the interface curvature approaches a constant. And in a zero Bond number system, it is a constant (i.e., this interface is a segment of a sphere). As the Bond number increases, the interface curvature along the tank centerline decreases and the interface approaches a flat surface. As the interface becomes more planar along the tank centerline, it also becomes more tightly curled near the tank wall in order to satisfy the constant angle requirement.

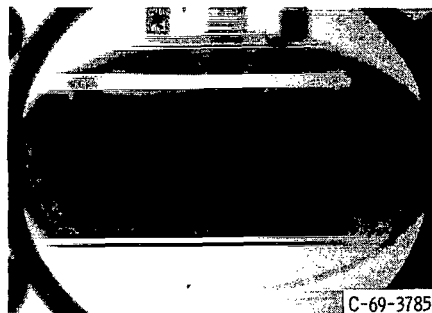
Although the effect of varying the system Bond number is similar when the liquid fill level is lower, the resulting shape will be quite different (as shown in fig. 4). For the higher eccentricity spheroids and low fill levels, as the Bond number is decreased and as the interface consequently approaches a spherical surface, the tank bottom becomes uncovered. The Bond number at which this transition to an annular type of interface occurs is a function of tank eccentricity and fill level (as previously discussed). As seen



Bond number, 1



Bond number, 10



Bond number, 30

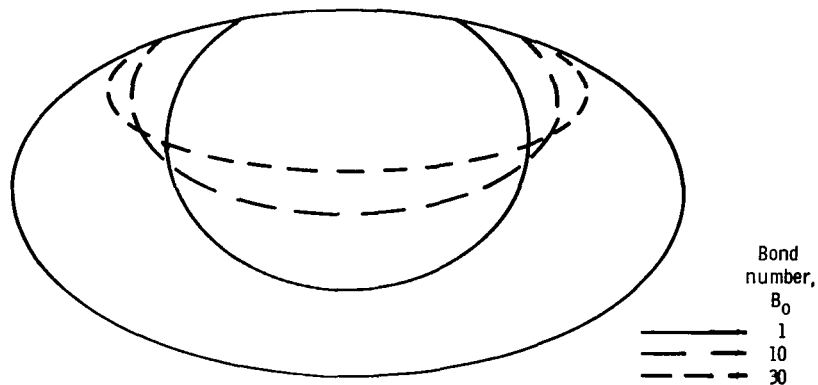
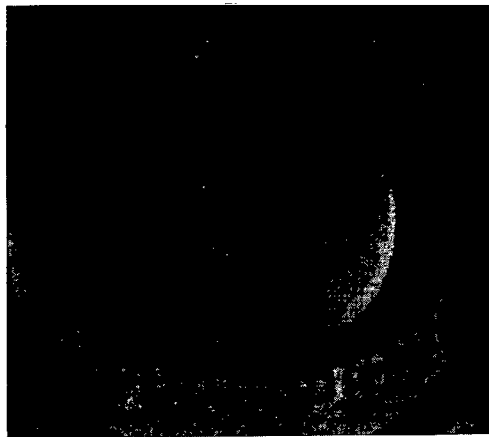


Figure 3. - Interface curvature as function of Bond number at high fill level. Eccentricity, 0.80; 75 percent filling.

from figure 4, this type of interface is the result of satisfying the near 0° contact angle condition (i.e., θ must remain at 0° , ref. 3) for a fixed volume while increasing the interface curvature as a function of decreasing Bond number. The curvature increases to a point where the interface can no longer intersect the tank wall in only one plane and still satisfy the contact angle requirement.

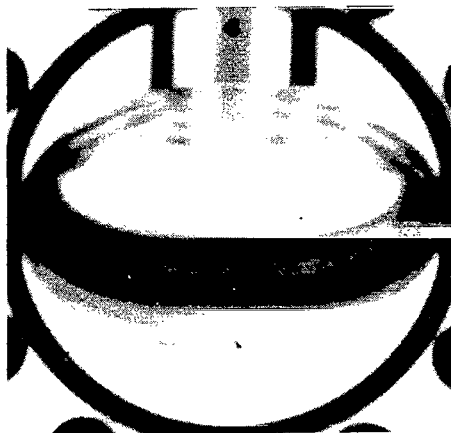
Effects of fill level. - The change in interface shape at fixed system Bond numbers as a function of fill level is shown in figures 5 and 6. At higher Bond numbers (fig. 5),



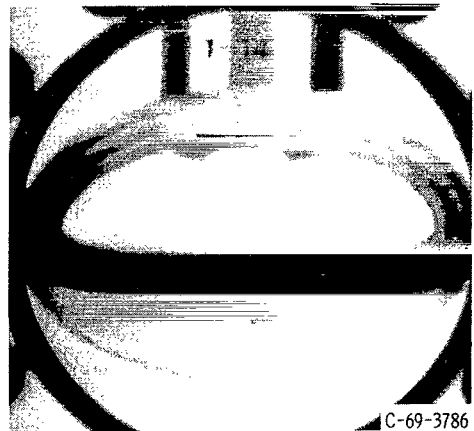
Bond number, 1



Bond number, 2



Bond number, 10



Bond number, 30

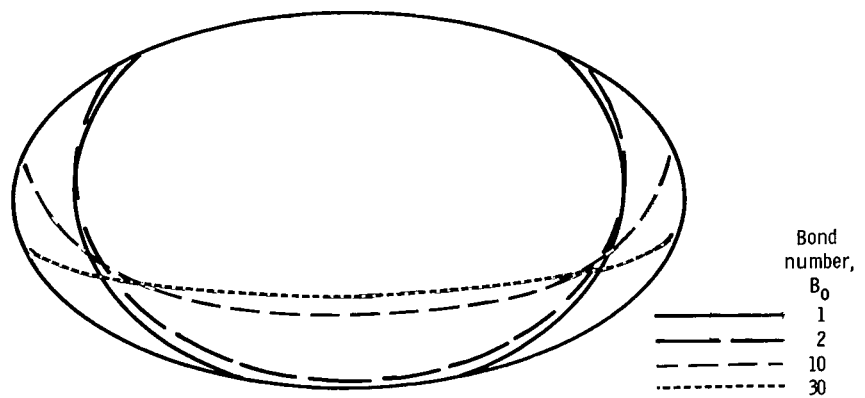
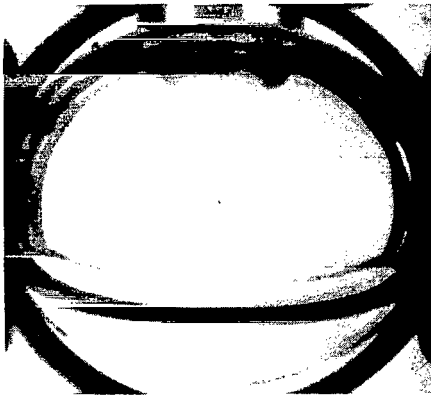
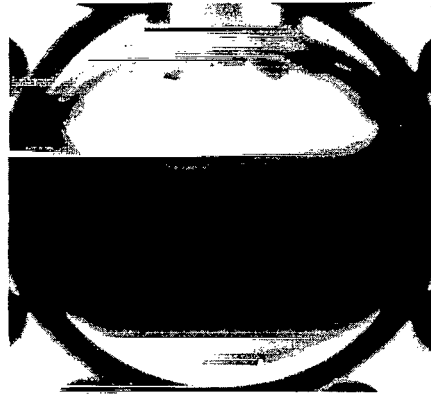


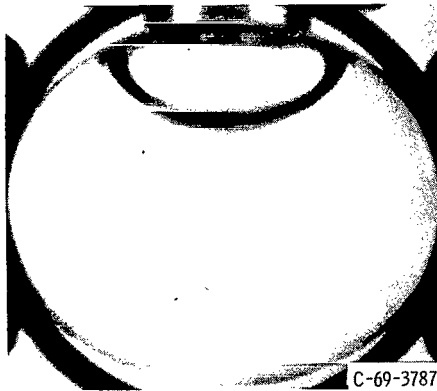
Figure 4. - Interface curvature as function of Bond number at low fill level. Eccentricity, 0.80; 25 percent filling.



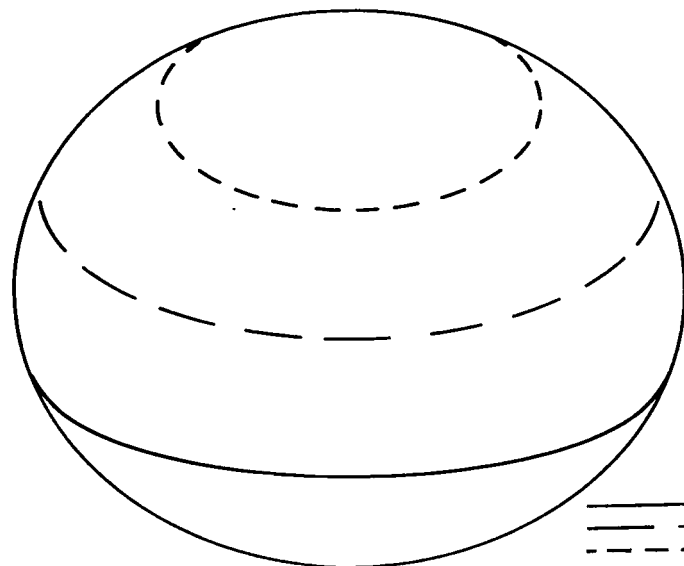
12.5 Percent filling



50 Percent filling

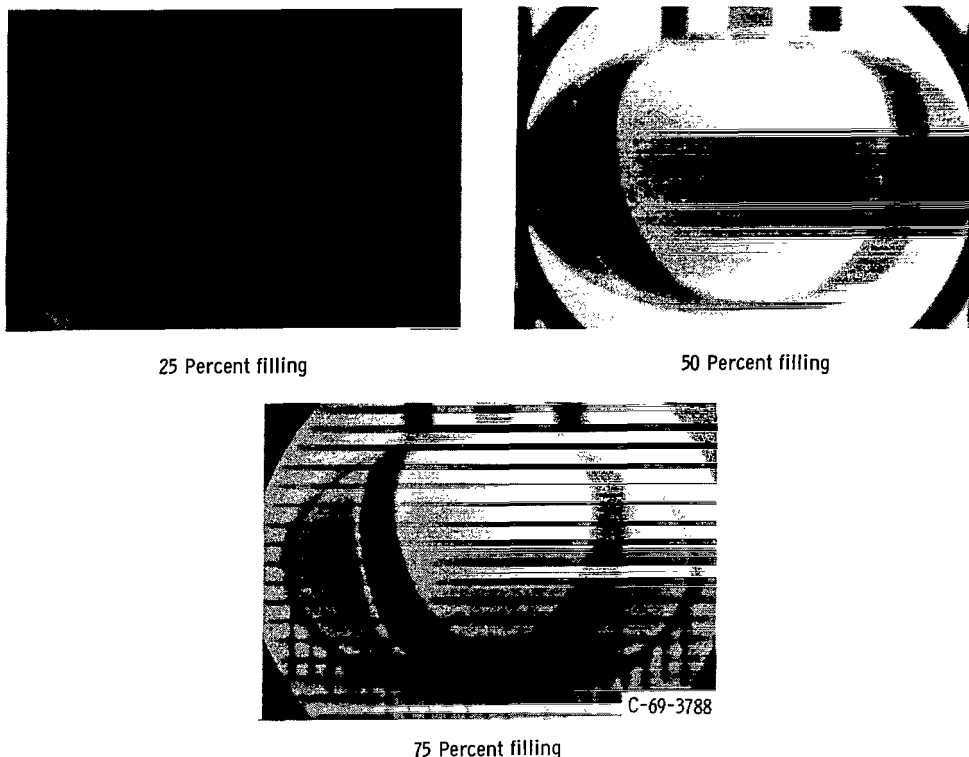


87.5 Percent filling



Percent
filling
12.5
50
87.5

Figure 5. - Interface curvature as function of fill level at Bond number of 10. Eccentricity, 0.50.



25 Percent filling

50 Percent filling

75 Percent filling

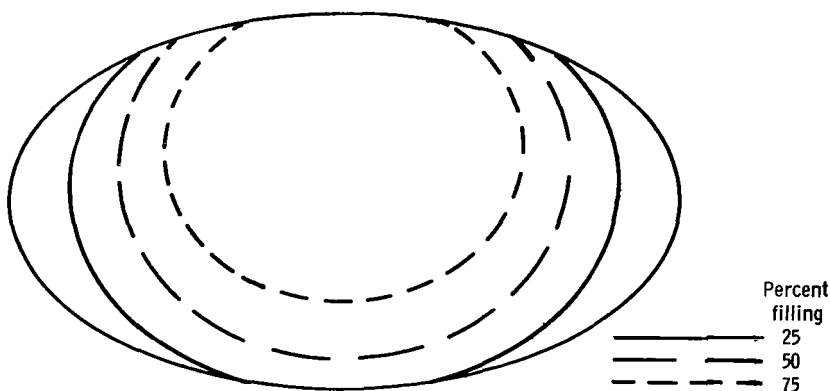


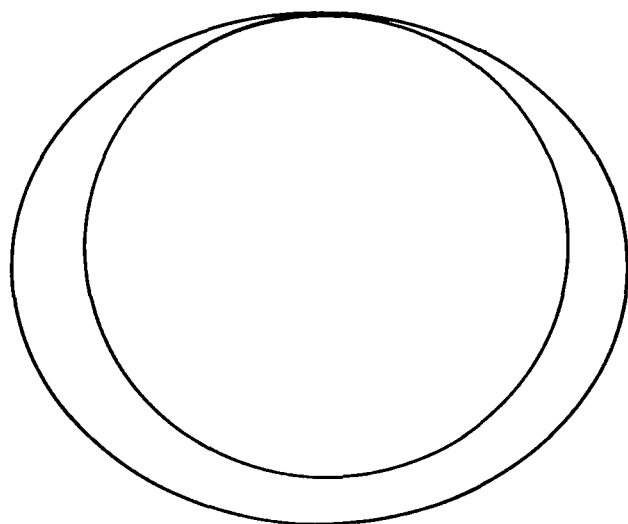
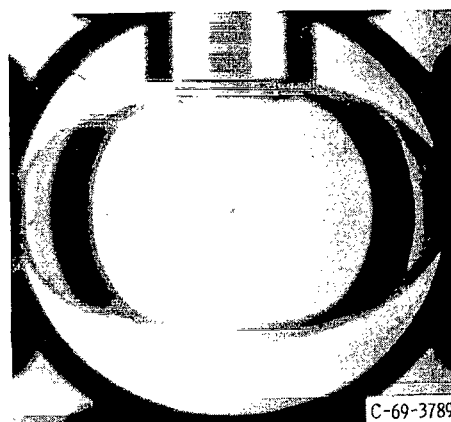
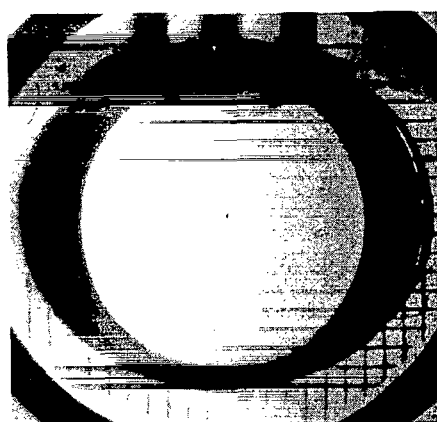
Figure 6. - Interface curvature as function of fill level at Bond number of 1. Eccentricity, 0.80.

the interface shape ranges from a relatively planar surface at the low fill levels to a flattened bubble at the high fill levels. Although the curvature along the tank minor axis does not vary significantly, a marked change does occur near the tank wall since at the higher fill levels the interface must curl back on itself (fig. 5) to satisfy the contact angle condition.

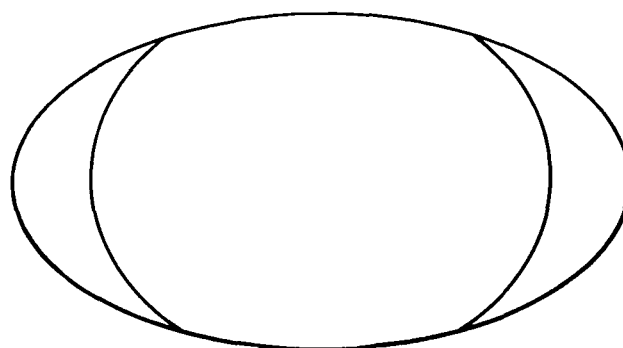
At lower Bond numbers (fig. 6), the shape of the interface is approaching the constant curvature of a spherical surface and a variation in the fill level simply changes the relative size of this surface. This change is significant when, in spheroids, the liquid

fill level is reduced to the point where the tank bottom is uncovered. As seen in figure 6, as the interface radius of curvature increases with decreasing fill level, it reaches a size where it can no longer intersect the tank wall in only one plane and still satisfy the contact angle condition. This, then, results in an annular interface.

Effects of tank eccentricity. - The degree of the spheroid eccentricity primarily influences the liquid-vapor interface shape in low Bond number, low fill level systems where annular type interfaces are possible. Figure 7 illustrates the primary effect of tank eccentricity. Here the fill level and Bond number are the same for both systems (37.5 percent fill level, $Bo = 0$) while only the tank eccentricity is varied (from 0.50 to 0.80). In both systems the interface has a constant curvature. In one case (0.50 eccen-



Eccentricity, 0.50



Eccentricity, 0.80

Figure 7. - Interface position as function of eccentricity. Bond number, 0; 37.5 percent filling.

tricity), the conditions are such that the spherical surface of the interface intersects the tank wall in one plane, but in the other (0.80 eccentricity), the contact angle and volume conditions require that its surface intersect the wall in two planes symmetric about the spheroid equator. This means that a complete prediction of the liquid-vapor interface configuration in spheroids requires not only a knowledge of the system Bond number and fill level but also a description of the tank eccentricity.

Effects of initial liquid position. - In the data discussed previously, the initial conditions of the system were such that the liquid was bottomed in the tank and symmetric about the tank minor axis before entry into the low-gravity test environment. In these tests, the resultant low Bond number interface was also symmetric about the tank minor axis even though in some cases the tank bottom was uncovered (see data in appendix). Although the initial position of the liquid (i.e., prior to entering a low-gravity environment) should have no effect on the equilibrium interface shape for finite Bond number systems, it could possibly influence the final shape in zero Bond number cases. This influence appears particularly feasible for the low fill level systems where annular interfaces can occur. In these cases, the uniqueness of the predicted symmetric interface shapes might be questioned.

Preliminary tests were conducted with the liquid initially positioned asymmetrically in the bottom of the tank. The result of one such test is presented in figure 8. The interface observed at the end of the 5-second test was quite different from the symmetric shape predicted. Although the interface shown in figure 8 did not appear to be moving at the end of the test, it cannot be stated with certainty that an equilibrium state had been reached. For the interface in figure 8 to be in a transient state, the formation time of such an asymmetric system must be exceedingly long, for, when the same system was

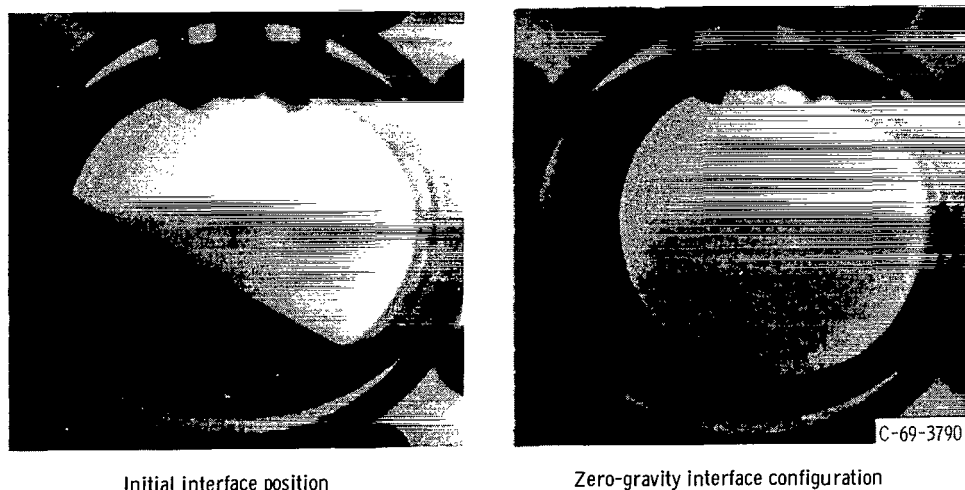


Figure 8. - Interface configuration resulting from initially asymmetric condition. Eccentricity, 0.50; 25 percent filling; Bond number, 0.

tested with an initially symmetric liquid position, only 2.50 seconds were required to attain a quiescent equilibrium interface shape which was symmetric about the tank semi-minor axis. In any case, there is a definite effect due to the initial liquid position, and further investigation will be necessary to determine its true nature.

SUMMARY OF RESULTS

An experimental investigation was conducted to study the static equilibrium liquid-vapor interface configuration in a spheroidal container in low-gravity environments. The study employed oblate spheroidal tanks with eccentricity values of 0, 0.50, 0.68, and 0.80 and semimajor axes of 2.0, 3.0, and 4.0 centimeters. Test liquids were restricted to those which possess near 0° static contact angles on the tank surfaces. Experiments were conducted in low-gravity environments ranging from 10^{-5} to 3.1×10^{-2} g which resulted in system Bond numbers ranging from effectively zero (i.e., approximately 0.001) to as high as 30. The study yielded the following results:

1. Measured interface configurations compared favorably with the analytical predictions of previous investigators.
2. At low Bond numbers, both the liquid fill level and the spheroid eccentricity become primary factors in determining the interface configuration.
3. At particular system combinations of low Bond numbers, low fill levels, and high spheroid eccentricities, neither the bottom of the tank nor the top of the tank is covered by liquid. In these cases, the liquid position is characterized by an annular type of interface covering the outer perimeter of the spheroid. The system combinations for which this type of interface occurs are as predicted in reference 5.
4. The initial position of the liquid prior to entry into a low-gravity environment has an effect on formation of the low-gravity liquid-vapor interface configuration.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 18, 1969,
124-09.

APPENDIX - QUANTITATIVE INTERFACE CONFIGURATION DATA

Plots of the experimentally measured liquid-vapor interface configurations and liquid edge positions are presented in figures 9 to 11. These data have been corrected for refraction distortions. The predicted interface configurations presented in these figures were obtained from reference 5. In addition to these data, qualitative observations were also made to compare the experimental results of this study with theoretical predictions.

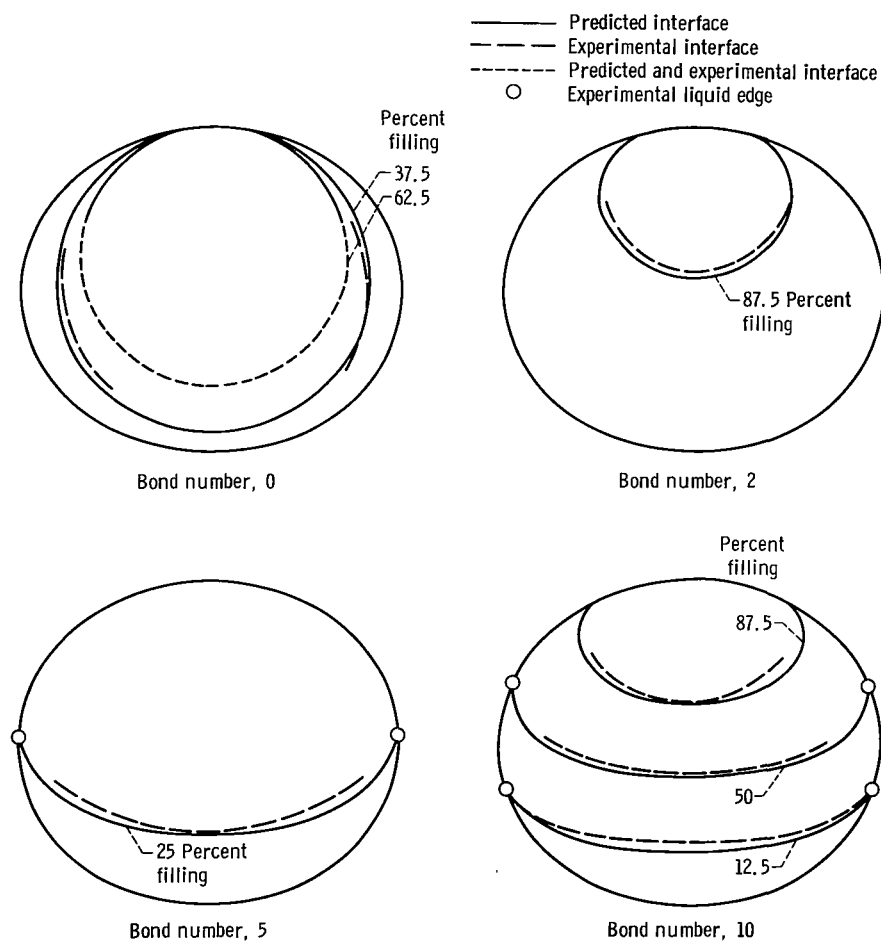


Figure 9. - Eccentricity, 0.50.

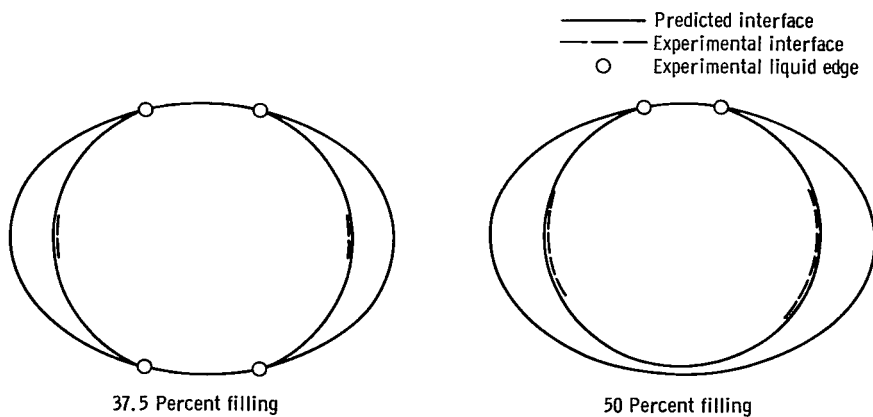


Figure 10. - Eccentricity, 0.68; Bond number, 0.

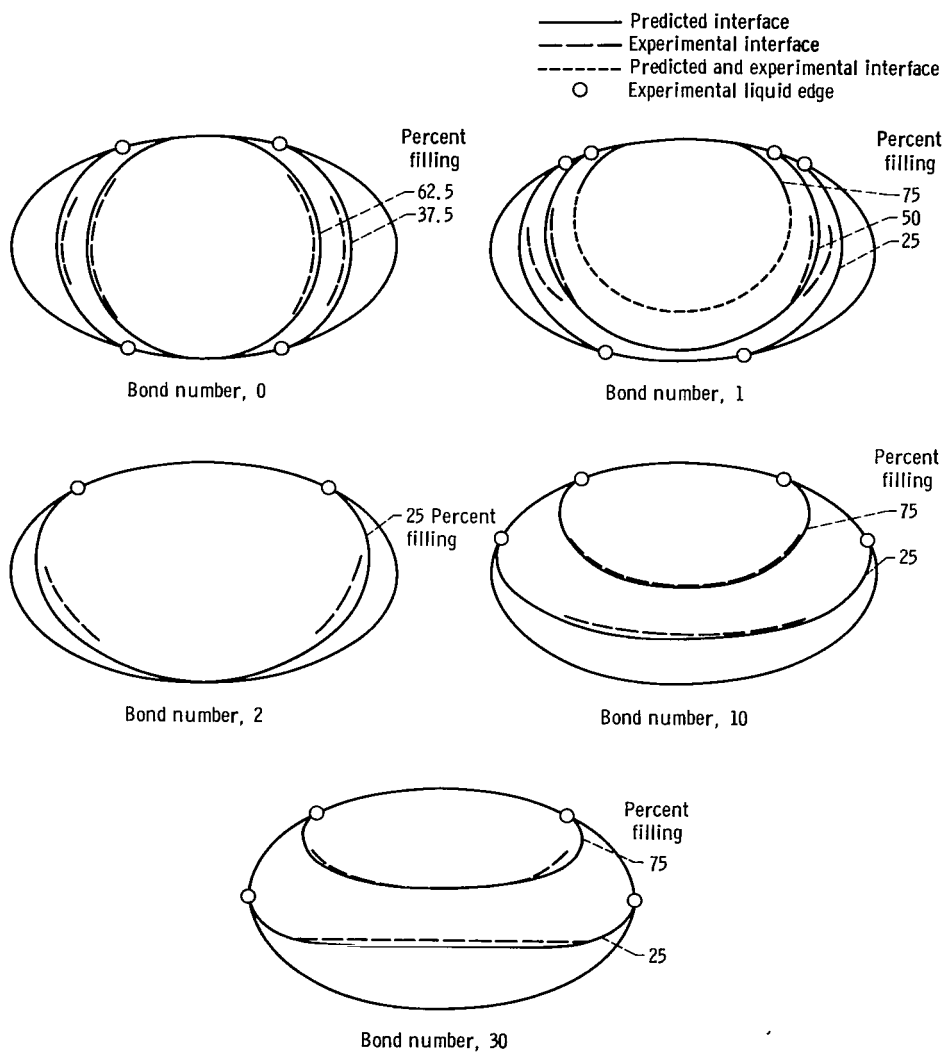


Figure 11. - Eccentricity, 0.80.

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